Higgs production in association with jets at the LHC

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HERA and the LHC DESY 15 March 2007
Feynman x’s for the production of a particle of mass M

\[ x_{1,2} = \left( \frac{M}{14 \text{ TeV}} \right) e^{\pm y} \]

\[ Q = M \]

\[
\begin{align*}
M &= 10 \text{ GeV} \\
M &= 100 \text{ GeV} \\
M &= 1 \text{ TeV} \\
M &= 10 \text{ TeV} \\
66y &= 40 \quad 224
\end{align*}
\]

\[ Q^2 = \left( \frac{M}{\text{GeV}^2} \right) 
\]
MRST 2001 PDF's

\[ x f(x, Q^2) \]

- Red: up
- Blue: down
- Magenta: antiup
- Cyan: antidown
- Orange: strange
- Green: charm
- Yellow: gluon

MRST2001

\[ Q^2 = 10 \text{ GeV}^2 \]
In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

- **gluon fusion** $gg \rightarrow H$
  - largest rate for all $M_H$
  - proportional to the top Yukawa coupling $y_t$

- **weak-boson fusion (WBF)** $qq \rightarrow qqH$
  - second largest rate (mostly $u \bar{d}$ initial state)
  - proportional to the $WWH$ coupling

- **Higgs-strahlung** $q\bar{q} \rightarrow W(Z)H$
  - third largest rate
  - same coupling as in WBF

- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher $x$ range
  - proportional to the heavy-quark Yukawa coupling $y_Q$
in the intermediate Higgs mass range  \( M_H \sim 100 - 200 \) GeV

- gluon fusion cross section is  \( \sim 20 - 60 \) pb
- WBF cross section is  \( \sim 3 - 5 \) pb
- \( WH, ZH, t\bar{t}H \) yield cross sections of  \( \sim 0.2 - 3 \) pb
**Weak Boson Fusion: \(qq \rightarrow qqH\)**

**WBF features**
- **Energetic jets** in the **forward** and **backward** directions
- **Higgs** decay products between the tagging jets
- Sparse gluon radiation in the central-**rapidity** region, due to colourless **W/Z** exchange
- **NLO** corrections increase the **WBF** production rate by about **10%**, and thus are small and under control
- **WBF** can be measured with good statistical accuracy: \(\sigma \times BR \approx \mathcal{O}(10\%)\)

\[\eta = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta}\]
**Signal Significance and \((\text{Stat} + \text{Syst})\) Error**

### ATLAS

- \(\int L\, dt = 30 \text{ fb}^{-1}\)
- \(\text{(no K-factors)}\)

#### QCD/p.d.f. uncertainties:
- \(\mathcal{O}(5\%)\) for WBF
- \(\mathcal{O}(20\%)\) for gluon fusion

#### Luminosity uncertainties:
- \(\mathcal{O}(5\%)\)

#### Statistical significance:
\[
\frac{N_S}{\sqrt{N_S + N_B}}
\]

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**Inclusive Higgs Production**

- **Solid**: gluon fusion
- **Dashed**: WBF
- **Dotted**: ttH

\[\Delta\sigma_H/\sigma_H = \sqrt{(N_S + N_B)/N_S}\]

200 fb\(^{-1}\) of data

**hep-ph/0203187**

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Cross sections at high $Q^2$

separate the short- and the long-range interactions through factorisation

$$
\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/A}(x_1, \mu_F^2) f_{b/B}(x_2, \mu_F^2)
\times \hat{\sigma}_{ab \to X} \left( x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)
\} \quad X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets, ...}
$$

$\hat{\sigma}$ is known as a fixed-order expansion in $\alpha_S$

$$
\hat{\sigma} = C \alpha^n_S (1 + c_1 \alpha_S + c_2 \alpha_S^2 + \ldots)
$$

$c_1 = \text{NLO} \quad c_2 = \text{NNLO}$

or as an all-order resummation

$$
\hat{\sigma} = C \alpha^n_S \left[ 1 + (c_{11} L + c_{10}) \alpha_S + (c_{22} L^2 + c_{21} L + c_{20}) \alpha_S^2 + \ldots \right]
$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

$c_{11}, c_{22} = \text{LL} \quad c_{10}, c_{21} = \text{NLL} \quad c_{20} = \text{NNLL}$
**Higgs Production via Gluon Fusion**

**Leading Order**

\[ \mathcal{O}(\alpha_s^2) \quad gg \rightarrow H \]

- energy scales: \( \hat{s} = M_H^2 \) and \( M_t^2 \)
Higgs Production via Gluon Fusion

Leading Order

$O(\alpha_s^2)$ \quad gg \rightarrow H

energy scales: \( \hat{s} = M_H^2 \) and \( M_t^2 \)

NLO Corrections

$O(\alpha_s^3)$

- 2-loop \( gg \rightarrow H \)
- 1-loop \( gg \rightarrow gH \quad qg \rightarrow qH \) \(+\) crossings

Djouadi, Graudenz, Spira, Zerwas, '93-'95

large \( K \) factor: \( \sigma^{\text{NLO}} = K^{\text{NLO}} \sigma^{\text{LO}} \) \( O(40 - 100\%) \)
THE LARGE TOP-MASS LIMIT

\[ M_H \ll 2M_t \]
The Large Top-Mass Limit

\[ M_H \ll 2M_t \]

NLO corrections

\[ K \text{ factor in the large } M_t \text{ limit} \]
\[ K_\infty = \lim_{M_t \to \infty} K \]

NLO rate in the large \( M_t \) limit
\[ \sigma_{\infty}^{\text{NLO}} = K_\infty^{\text{NLO}} \sigma^{\text{LO}} \]
\( \sigma_{\infty}^{\text{NLO}} \) is within \( 10\% \) of \( \sigma^{\text{NLO}} \) for \( M_H \lesssim 1 \) TeV
gg → H \textbf{IN THE LARGE } M_t \textbf{ LIMIT}

NNLO CORRECTIONS \hspace{2cm} O(\alpha_S^4)

2-loop

\hspace{1cm} gg \rightarrow H \hspace{1cm} qg \rightarrow qH + \text{crossings}

1-loop

\hspace{1cm} gg \rightarrow ggH \hspace{0.5cm} qg \rightarrow qgH \hspace{0.5cm} qQ \rightarrow qQH + \text{crossings}

R. Harlander  hep-ph/0007289

The band contours are

lower \hspace{1cm} \mu_R = 2M_H \hspace{0.5cm} \mu_F = M_H/2

upper \hspace{1cm} \mu_R = M_H/2 \hspace{0.5cm} \mu_F = 2M_H

total cross section for inclusive Higgs production at LHC

Harlander Kilgore 02
Anastasiou Melnikov 02
Ravindran Smith van Neerven 03
The properties of the Higgs-like resonance are its couplings: gauge, Yukawa, self-couplings. Quantum numbers: charge, colour, spin, CP.

The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events.
$H + 2$ JETS RATE as a function of $M_H$

$\mu_F = \sqrt{p_{j1\perp}p_{j2\perp}}$, $\mu_R = M_Z$

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0105129

$\sigma$ (pb)

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>solid $m_t=175$ GeV</th>
<th>dots $m_t \to \infty$</th>
<th>dashes WBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
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<tr>
<td>200</td>
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<td>300</td>
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<tr>
<td>500</td>
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<tr>
<td>600</td>
<td></td>
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</tbody>
</table>

inclusive cuts:

\[ p_{j\perp} > 20 \text{ GeV} \]
\[ |\eta_j| < 5 \]
\[ R_{jj} > 0.6 \]

WBF cuts: incl. +

\[ |\eta_{j1} - \eta_{j2}| > 4.2 \]
\[ \eta_{j1} \cdot \eta_{j2} < 0 \]
\[ \sqrt{s_{jj1j2}} > 600 \text{ GeV} \]

WBF cuts enhance WBF wrt gluon fusion by a factor 10
**Scale Dependence**

renormalisation $\mu_R$ & factorisation $\mu_F$ scales

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0108030

\[ \mu_R = \xi \mu_0, \quad \mu_F = \sqrt{p_{j1\perp} p_{j2\perp}} \]

\[ \mu_F = \xi \mu_0, \quad \mu_R = M_Z \]

![Graphs showing scale dependence](image)

- **strong $\mu_R$ dependence:** the calculation is LO and $O(\alpha_S^4)$
- **a natural scale for $\alpha_S$?**
  - high energy limit suggests $\alpha_S^4 \rightarrow \alpha_S(p_{j1\perp}) \alpha_S(p_{j1\perp}) \alpha_S^2(M_H)$
  - $\sigma$ varies by a factor 2.5 for $\mu_0/2 < \mu_R < 2\mu_0$
- **mild $\mu_F$ dependence:** $O(10\%)$ over the $\mu_0/5 < \mu_R < 5\mu_0$ range
NLO corrections

NLO corrections increase the WBF production rate by about 10%, with a few % change under $\mu_R$ scale variation

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003
Berger Campbell 2004

NLO corrections in the large $M_{top}$ limit increase the gluon fusion production rate by about 15--25%, but the change under $\mu_R$ scale variation is sizeable

Campbell, Ellis, Zanderighi 2006
\[ \Delta \eta_{jj} : \text{rapidity difference between the two jets} \]

\[ \frac{d\sigma}{d\Delta \eta_{jj}} (\text{pb}) \]

solid: gluon fusion
dashes: WBF

\[ m_H = 120 \text{ GeV} \]
\[ m_t = 175 \text{ GeV} \]

\[ \Delta \eta_{jj} \]

inclusive cuts:
\[
\begin{align*}
    p_{j\perp} &> 20 \text{ GeV} \\
    |\eta_j| &< 5 \\
    R_{jj} &> 0.6
\end{align*}
\]

WBF cuts: incl. +
\[
\begin{align*}
    \eta_{j_1} \cdot \eta_{j_2} &< 0 \\
    \frac{1}{\sqrt{s_{jj}}} &> 600 \text{ GeV}
\end{align*}
\]

- WBF events spontaneously have a large \( \Delta \eta_{jj} \)
- dip in gluon fusion at low \( \Delta \eta_{jj} \) is unphysical: \( R_{jj} = \sqrt{\Delta \eta_{jj} + \Delta \phi_{jj}} > 0.6 \)
$\Delta \phi_{jj} \equiv$ the azimuthal angle between the two jets

$A_{WWBF} \sim \frac{1}{2p_1 \cdot p_4 - M_W^2} \frac{1}{2p_2 \cdot p_3 - M_W^2} \hat{s}m_{jj}^2$

\( \Rightarrow \) a flat $\Delta \phi_{jj}$ distribution

gluon fusion in the large $M_t$ limit

$L_{eff} = \frac{1}{4} A H G_{\mu\nu} G^{\alpha \mu\nu} \quad A = \frac{\alpha_s}{3\pi v}$

$A_{gluon} \sim J_1^\mu (q_1^{\nu} q_2^{\mu} - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu$

$J^\mu \equiv$ quark-gluon current

for $|p_i^z| \gg |p_i^{x,y}| \quad i = 3, 4$: forward jets

$A_{gluon} \sim (J_1^0 J_2^0 - J_1^3 J_2^3) p_{3\perp} \cdot p_{4\perp}$

\( \Rightarrow \) zero at $\Delta \phi_{jj} = \frac{\pi}{2}$
the azimuthal angle distribution discriminates between WBF and gluon fusion

note that the large $M_t$ limit curve approximates very well the exact curve
Parton showering and hadronisation are modelled through shower Monte Carlos (HERWIG o PYTHIA)
### 3 complementary approaches to $\hat{\sigma}$

<table>
<thead>
<tr>
<th></th>
<th>matrix-elem MC’s</th>
<th>fixed-order x-sect</th>
<th>shower MC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>final-state description</td>
<td>hard-parton jets. Describes geometry, correlations, ...</td>
<td>limited access to final-state structure</td>
<td>full information available at the hadron level</td>
</tr>
<tr>
<td>higher-order effects:</td>
<td>hard to implement: must introduce negative probabilities</td>
<td>straightforward to implement (when available)</td>
<td>included as vertex corrections (Sudakov FF's)</td>
</tr>
<tr>
<td>loop corrections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>higher-order effects:</td>
<td>included, up to high orders (multijets)</td>
<td>straightforward to implement (when available)</td>
<td>approximate, incomplete phase space at large angles</td>
</tr>
<tr>
<td>hard emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>resummation of large logs</td>
<td>?</td>
<td>feasible (when available)</td>
<td>unitarity implementation (i.e. correct shapes but not total rates)</td>
</tr>
</tbody>
</table>

M.L. Mangano KITP collider conf 2004
Shower MonteCarlo generators

**HERWIG**  B. Webber et al. 1992

being re-written as a C++ code (HERWIG++)

**PYTHIA**  T. Sjostrand 1994

and more

**CKKW**  S. Catani F. Krauss R. Kuhn B. Webber 2001

a procedure to interface parton subprocesses with a different number of final states to parton showers

**MC@NLO**  S. Frixione B. Webber 2002

a procedure to interface NLO computations to shower MC’s
Azimuthal angle distribution

Including **parton showers** and **hadronisation** through **HERWIG**, Odagiri finds much less correlation between the jets

**Caveat!**

the plot has been obtained by generating also the jets through the showers
Matrix-element MonteCarlo generators

multi-parton generation: processes with many jets (or W/Z/H bosons)

COMPHEP   A. Pukhov et al. 1999
GRACE/GR@PPA    T. Ishikawa et al. K. Sato et al. 1992/2001
HELAC     C. Papadopoulos et al. 2000

processes with 6 final-state fermions

PHASE      E. Accomando A. Ballestrero E. Maina 2004

merged with parton showers

all of the above, merged with HERWIG or PYTHIA

SHERPA    F. Krauss et al. 2003
Azimuthal angle distribution

**ALPGEN:** $H + 2$ jets at parton level + parton shower by HERWIG

VBF cuts

$p_{Tj}^{tag} > 30$ GeV \quad $|\eta_j| < 5$ \quad $R_{jj} > 0.6$

$|\eta_{j1} - \eta_{j2}| < 4.2$ \quad $\eta_{j1} \cdot \eta_{j2} < 0$

$m_{jj} > 600$ GeV

$A_\phi$: a quantity that characterises how deep the dip is

<table>
<thead>
<tr>
<th>$A_\phi$</th>
<th>parton level</th>
<th>shower level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH + 2$ jets</td>
<td>0.474(3)</td>
<td>0.357(3)</td>
</tr>
<tr>
<td>$VBF + 2$ jets</td>
<td>0.017(1)</td>
<td>0.018(1)</td>
</tr>
</tbody>
</table>

$A_\phi = \frac{\sigma(\Delta\phi < \pi/4) - \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}{\sigma(\Delta\phi < \pi/4) + \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}$

$\Delta\Phi$ is the azimuthal angle between the tagging jets
Normalised jet multiplicity after parton shower for H + 2 (solid) and 3 (dashes) partons. Solid curve is normalised to the total x-sect for H + 2 jets.

Note the log scale on the rhs panel.

VBF cuts

\[ p_{Tj}^{tag} > 30 \text{ GeV} \quad p_{Tj} > 20 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} > 0.6 \]
\[ |\eta_{j1} - \eta_{j2}| < 4.2 \quad \eta_{j1} \cdot \eta_{j2} < 0 \quad m_{jj} > 600 \text{ GeV} \]
the azimuthal angle $\Delta \phi_{jj}$ between the jets can be used as a tool to investigate the tensor structure of the WWH coupling

Plehn, Rainwater, Zeppenfeld hep-ph/0105325

take a gauge-invariant effective Lagrangian with dim. 6 operators (CP even and CP odd) describing an anomalous WWH coupling

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_{e,6}^2} (\Phi^\dagger \Phi) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda_{o,6}^2} (\Phi^\dagger \Phi) \tilde{V}_{\mu\nu} V^{\mu\nu}$$

expand $\Phi$ about the vev (get dim. 5 (D5) operators)

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H W^{++}_\mu W^{-\mu}_\nu + \frac{1}{\Lambda_{o,5}} H \tilde{W}^{++}_\mu W^{-\mu}_\nu \quad \text{with} \quad \frac{1}{\Lambda_5} = \frac{g^2 v}{\Lambda_6^2}$$

CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling

zero at $\Delta \phi_{jj} = 0, \pi$

CP even D5 operator is like the effective $ggH$ coupling

$$\mathcal{A}_{\text{CP even}} \sim \frac{1}{\Lambda_{e,5}} J_1^\mu (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu \quad \Rightarrow \quad \text{zero at} \quad \Delta \phi_{jj} = \frac{\pi}{2}$$
AZIMUTHAL ANGLE DISTRIBUTION FOR WWH COUPLINGS

- assume a Higgs-like scalar signal is found at LHC at the SM rate (for D5 operators: $\Lambda_5 \sim 500$ GeV)

![Azimuthal Angle Distribution](image)

WBF cuts:
- $p_{j\perp} > 20$ GeV
- $|\eta_j| < 5$
- $R_{jj} > 0.6$
- $\eta_{j_1} \cdot \eta_{j_2} < 0$
- $|\eta_{j_1} - \eta_{j_2}| > 4.2$

- the $\Delta \phi_{jj}$ distribution
  - discriminates between different WWH couplings
  - is independent of the particular decay channel and the Higgs mass range
**Interference effects in the $\Delta \phi_{jj}$ distribution**

- Assume a Higgs candidate is found at LHC with a predominantly SM $g^{\mu\nu}$ coupling. How sensitive are experiments to any D5 terms?
- No interference between SM and CP odd D5 operator.

\[
\frac{d\sigma}{d\Delta \phi_{jj}} (H \to \tau\tau) \text{ [fb]}
\]

$m_H = 120 \text{ GeV}$

\[\Delta \phi_{jj}\] distribution for the SM and interference with a CP even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{SM} = 0.04, 1.0$. Error bars correspond to an integrated luminosity of $100 \text{ fb}^{-1}$ per experiment, distributed over 6 bins, and are statistical only.

- Interference between SM and CP even D5 operator: $|A|^2 = |A_{SM} + A_{e,5}|^2$
  - All terms, but $|A_{SM}|^2$, have an approximate zero at $\Delta \phi_{jj} = \pi/2$
  - Systematic uncertainty induced by $H + 2$ jet rate from gluon fusion
  - $HG_{\mu\nu}G^{\mu\nu}$ is a CP even D5 operator
In WBF no colour is exchanged in the $t$ channel.

The central-jet veto is based on the different radiation pattern expected for WBF versus its major backgrounds, i.e. $t\bar{t}$ production and $WW + 2$ jet production.

The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF.

Barger, Phillips & Zeppenfeld hep-ph/9412276
Distribution in rapidity of the third jet wrt to the rapidity average of the tagging jets.

Ratio of Higgs + 3 jet to Higgs + 2 jet production as a function of $p_T^{\text{min}}$.
CONCLUSIONS

Once a Higgs-like resonance is found at the LHC, we shall want to study its couplings and quantum numbers.

In Higgs + 2 jets, the azimuthal angle correlation between the two jets can be used as a tool to distinguish between WBF and gluon fusion, and to investigate the tensor structure of the WWH coupling.

Because of the characteristic final-state topology induced by WBF production large-rapidity cuts can be used to deplete gluon fusion wrt WBF.

We examined Higgs + 2 jet-production through matrix-element MC’s, which include shower effects.

the analysis confirms the one at the parton level.

however, in gluon fusion large fraction of events with 3 or more jets

→ need a CKKW-type analysis